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Schemes for Producing High Intensity Low-longitudinal Emittance Proton Bunches for the Tevatron Collider

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DRAFT

Abstract:

I describe here very promising schemes for producing high intensity low longitudinal emittance proton bunches for proton-antiproton collider operation in the Tevatron. These methods are based on the use of wide-band barrier rf systems in the Main Injector. The beam dynamics simulations clearly suggest that these schemes allow a wide range of bunch intensities and longitudinal emittances. I also discuss a method, called “27 GeV coalescing”, which is a spin-off from 2.5 MHz pbar acceleration scheme demonstrated in the Main Injector (MI). Preliminary results from beam study for this scheme are presented. In this paper I present the principle of these methods and results of multi-particle beam dynamics simulations.

I Introduction and motivation

The Fermilab Tevatron will continue to be the highest energy hadron collider in the world till the LHC at CERN comes in to operation late in the decade. Therefore, it is vital to utilize the Tevatron facility as efficiently as possible during the next few years and beyond. In view of this, Fermilab Run II upgrade plans [1] are in place and have led to many improvements in the collider performances. The primary goal of the Run II upgrade plan is to maximize the integrated luminosity delivered to the collider experiments CDF and D0, dedicated to research in elementary particle physics. In this effort, delivering low emittance high intensity proton and antiproton beam bunches to the Tevatron is crucial.

The Run II design goal for the peak luminosity at the Tevatron is 29×10^{31}cm^{-2}sec^{-1} [1]. The instantaneous luminosity at each experiment is given by,

$$L = \frac{\gamma}{2\pi} f_0 B N_p N_{pbar} \frac{H}{\beta^* \varepsilon_p \left\{ 1 + \frac{\varepsilon_{pbar}}{\varepsilon_p} \right\}} \tag{1}$$

where γ ($\approx$1044) is the ratio of relativistic energy to the rest mass energy of proton. f_0 is the revolution frequency of the beam particles in the Tevatron ($\approx$47746 Hz), B is the number of bunches (=36) of each type. N_p and N_{pbar} are respectively number of proton and antiprotons in each bunch. β^* and ε s are the lattice parameter ($\approx$35 cm) and the transverse emittance of proton and antiprotons at collision, respectively. The quantity H is hourglass factor which depends on the longitudinal emittance of each bunch via the bunch length. The dependence of the luminosity on H is fairly weak. However, it is important to keep the longitudinal emittance to a minimum value (determined by the beam-beam interaction in the Tevatron) at injection in to the Tevatron because a smaller emittance beam gives better beam transmission through acceleration from 150 GeV to 980 GeV in the Tevatron. Additionally, a shorter interaction region (i.e., smaller longitudinal emittance) gives better collision coverage at the collider detectors.

Thus by increasing N_p and N_{pbar}, decreasing ε s and longitudinal emittances helps to produce higher instantaneous luminosity.

For the past one and half decades at Fermilab, the method for providing intense proton and antiproton bunches has been by coalescing a number of 53 MHz bunches at 150 GeV [2,3], earlier, in the Main Ring and since 2000 in the Main Injector [4]. Presently, ~300×10^9proton/bunch with a longitudinal emittance about 2.5 eVs/bunch and with transverse emittance of about 17π-mm-mr will be transferred to the Tevatron. In the case of anti-protons, ~50×10^9antiprotons/bunch with ≥ 2.5 eVs/bunch and ≤10π-mm-mr will be transferred. Further, a few percent of dc beam will also be transferred to the Tevatron on every shot. However, it is quite challenging to meet both intensity and emittance requirements for the collider operation (for example for protons, bunch intensity >270×10^9p/bunch with <2 eVs/bunch) with the current coalescing. Besides, if any further increase in the bunch intensity is needed, then large increase in the longitudinal emittance is unavoidable.

Significant effort is underway to inject high intensity low emittance anti-protons to the Tevatron [5, 6]. In the case of proton, similar effort is needed. We loose >10% of the protons from injection to collision [7,8]. This loss can be significantly reduced by injecting bunches with 30% lower longitudinal emittance. (However, if the longitudinal emittance is reduced significantly the intra-beam scattering would adversely affect the luminosity life-time.) It is estimated that by improving the quality of the proton beam from 250×10^9p/bunch at 3 eVs to 300×10^9p/bunch at 2 eVs at collision the peak luminosity is increased by >20%. (Here I assume a scenario of B =36 with transverse emittance of 17π-mm-mr for both protons and anti-protons, 40×10^9pbar/bunch at 3 eVs, β^* = 35 cm).

Recently, a new method for producing intense but shorter proton bunches for the Tevatron collider was proposed and tested [9]. In this method, the central region of 53 MHz bunches are captured in a series of 53 MHz rf manipulations while rejecting the rest and, the MI 2.5 MHz rf system is used for final coalescing similar to ref 2. All of these rf manipulations were carried out done at 8 GeV in the MI, below transition energy. Initial beam tests conducted in the Main Injector showed that one can achieve a longitudinal emittance of about 0.5 eVs (a factor of five smaller than Run II requirements). However, studies revealed a few limitations of this method: 1) achieved maximum intensity in the central bunch was around 150×10^{9} protons/53MHz bunch, which is about a factor of two smaller than that needed for collider (also had about 10% of the beam captured in the satellites), 2) the method is very much dependent on the quality of the 53 MHz proton bunches from the Booster. Therefore this scheme has not been pursued further.

During September-October 2003, the MI broad-band rf system [10] was installed. Bill Foster [11] and I independently thought that it might be possible to develop a scheme to produce bright 53 MHz proton bunches using MI broad-band rf system for the Tevatron collider shots. In this report, I propose three fully developed schemes to produce high intensity low-longitudinal beam bunches. All three schemes demand coalescing to be carried out above MI transition energy. The first two schemes use MI barrier rf systems. I describe here the principle and results of multi-particle beam dynamics simulations for these schemes. The feasibility and merits are also discussed. The third scheme "27 GeV coalescing" is a spin-off from the 2.5 MHz pbar acceleration scheme [6].

II Producing Intense Proton Bunches in the Main Injector

a) Barrie Bucket Scheme -1:

The concept of barrier beam coalescing outlined below incorporates the basic principles of longitudinal momentum mining [12] and adiabatic compression [13]. This method uses of rectangular barrier buckets. The principle of this scheme is illustrated schematically in figure 1. A number of 53 MHz bunches are accelerated in the MI from 8 GeV to 27 GeV, above the MI transition energy. At 27 GeV the momentum spread, $\frac{\Delta p}{p}$, of the bunches are reduced adiabatically by lowering the 53 MHz bucket height so that the bucket is completely full as shown in Fig. 1a . At this stage two small rectangular barrier pulses are opened encompassing the partly debunched bunches along with a large barrier bucket as shown in figure. 1b. At the same time, we turn off the 53 MHz rf system in the MI and start adiabatic barrier compression. The size of the small barrier pulses are chosen so that the total bucket area with zero barrier spacing is identical to the beam area needed at 150 GeV before injection into the Tevatron. The half height of the small barrier bucket is given by [13],

$$\Delta E_{small} = \sqrt{\frac{2\beta^2 eV_{small} T_{small} E_0}{T_0 |\eta|}} \qquad (2)$$

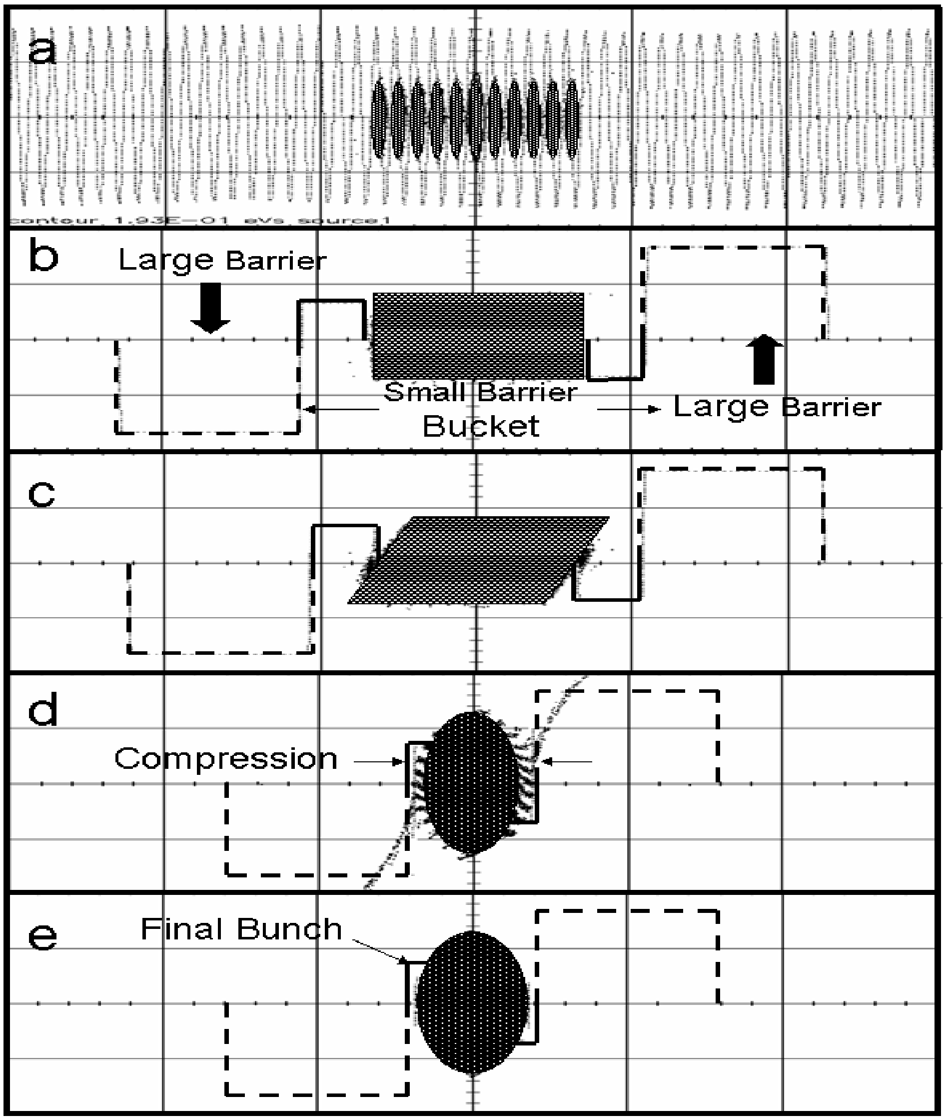


Figure 1: Schematic view of barrier bucket beam coalescing, Scheme-1: a) Beam in 53 MHz buckets, b) beam after debunching between two barrier buckets: "Small Barrier Bucket" and Large Barrier Buckets (indicated by arrows), c) beam shearing, high momentum particles start penetrating through the small barriers, also barrier compression starts at this stage, d) a stage of adiabatic beam compression (particles not fitting in the small barrier buckets are being removed), e) final bunch comprising of high density, low emittance beam of bunch area set by the small barrier bucket.

where η, T_0 and β are the phase slip factor, the revolution period and the ratio of the particle velocity to that of light, respectively. E_0 is the synchronous energy of the beam particles. V_{small} and T_{small} are barrier pulse height and the pulse width of the small barrier bucket, respectively. e is the electron charge. In the absence of restoring force from 53 MHz rf wave, bunches start shearing inside the small barrier (see Fig. 1c) if they are not fully debunched. The particles with momentum spread larger than ΔE_{small} will escape from the region, as shown in the Fig.1d. When the gap between the smaller pulses is zero, we stop bunch compression. The longitudinal emittance of the trapped particles in the smaller bucket is given by [14],

$$\varepsilon_{small} = \frac{4T_0|\eta|\Delta E_{small}{}^3}{(3\beta^2 E_0 eV_{Small})} \tag{3}$$

The beam particles in the smaller barrier bucket are transferred to a 53 MHz bucket. In case the bunch width is too large then the bunch is captured in 2.5 MHz bucket first and after a bunch manipulation the beam particles are transferred to 53 MHz bucket adopting a method described in ref. 6. Finally, the single bunch will be accelerated to 150 GeV in the MI.

An alternative method for beam compression of the de-bunched beam between barrier buckets is “barrier flip-flop technique” [15] instead of adiabatic compression. This will reduce the compression time with out changing the final results.

b) Barrier Bucket Scheme-2:

In this scheme, the 53 MHz bunches are accelerated to 27 GeV similar to “Barrier Bucket Scheme-1”. At 27 GeV, the momentum spread of the bunches are reduced adiabatically by lowering the 53 MHz bucket height. At this stage each bunch is captured in a rectangular barrier bucket. The mismatch between 53 MHz bucket and the rectangular barrier bucket is expected to give a small emittance growth. Further, a large barrier bucket is also opened as shown in figure 2A. (similar to Scheme-1). Subsequently, the bunches are merged adiabatically by lowering the barrier heights for the intermediate buckets except the last two small barriers on both sides as shown in figure 2B. By this technique we can keep longitudinal emittance growth to minimum [16]. The high momentum particles which do not fit in this barrier will be removed by large barrier similar to Scheme-1. The phase-space area of the captured beam particles is given by [14],

$$\varepsilon_{small} = \frac{4T_0|\eta|\Delta E_{small}{}^3}{(3\beta^2 E_0 eV_{Small})} + 2T_{gap}\Delta E_{small} \qquad (4)$$

where T_{gap} is the space between the small barriers. The bunch in the barrier bucket will be captured in 53MHz bucket after a bunch rotation in 2.5 MHz bucket and finally the single bunch will be accelerated to 150 GeV.

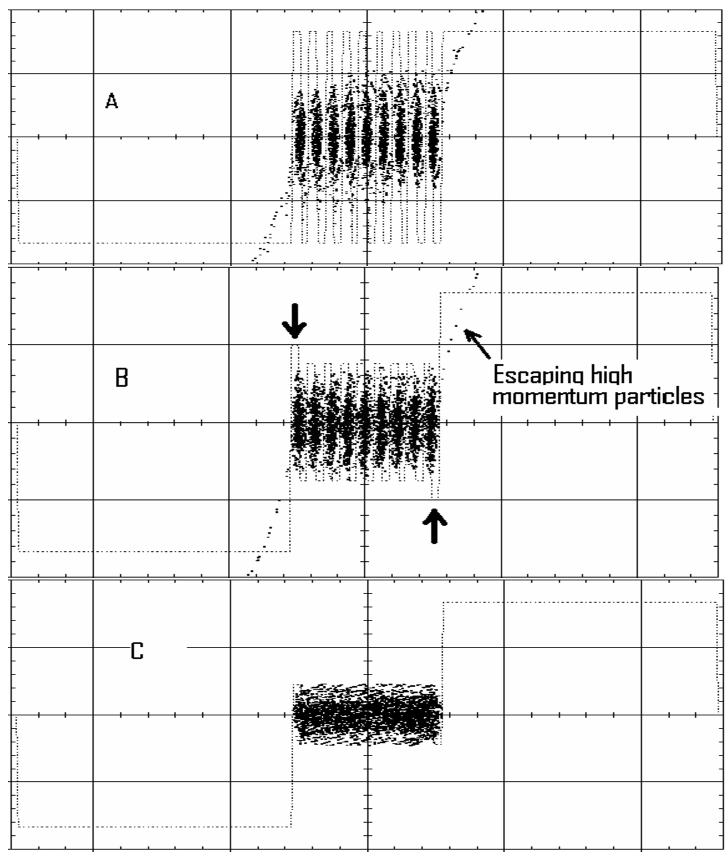


Figure 2: Schematic view of barrier bucket beam coalescing Scheme-2: A) Beam in nine 53 MHz buckets transferred to rectangular barrier buckets. B) adiabatic merging of the bunches, C) final bunch before transfer to 2.5MHz bucket for bunch rotation and 53MHz capture.

c) Coalescing at 27 GeV:

In this method, about seven 53 MHz bunches of 50×10^9 protons each are accelerated in the MI from 8 GeV to 27 GeV. The longitudinal emittance of each bunch is assumed to be about 0.15 eVs. The bunch coalescing is carried out at 27 GeV (instead of at 150 GeV [2]). The final single intense 53 MHz bunch is accelerated from 27 GeV to 150 GeV before it is transferred to the Tevatron. In this scheme, the selection of the energy where coalescing is done is quite arbitrary as long as it is above the transition energy of the MI. By carefully limiting the bucket area of either accelerating bucket at a point from 27 GeV to 150 GeV one can select the longitudinal emittance to a desired value of 2 eVs or less.

III Theoretical simulations and feasibility of the techniques

Beam dynamics simulations have been carried out for the Main Injector machine parameters for all three schemes using multi-particle beam dynamics simulation code ESME [17] to test the feasibility of the techniques. The Table 1 describes the MI machine parameters. The longitudinal emittance of the proton bunches were taken to be in the range of 0.1 eVs to 0.3 eVs. The MI acceleration ramp used for the simulation is given in the Table 2. Here, we first discuss the results of simulations for the barrier bucket coalescing schemes and then that for the 27 GeV coalescing case.

III.1 Barrier Bucket Coalescing Scheme -1:

Simulations for this case are carried out by changing variety of parameters like number of injected bunches, bunch distributions etc. The number of bunches at 8 GeV injection were in the range of 9-15 with each bunch assume to have a bi-Gaussian, parabolic or an elliptic distribution. In reality, the bunches from the Fermilab Booster resemble shape between parabolic and bi-Gaussian shape.

First, the 53 MHz beam bunches are accelerated from 8 GeV to 27 GeV. At the 27 GeV front-porch, the 53MHz buckets are reduced from about 0.5 MV to a value in the range of 1 kV to 10 kV iso-adiabatically in about 0.5 sec and 53MHz rf system is turned off. Subsequently, two barrier buckets are opened and started beam compression as explained in Section IIa. The pulse width T_{small} is selected to be about 57 nsec and that for the large barrier bucket it was about 310 nsec. The V_{small} is varied in the range of 340 V (to produce 1.5 eVs bunches to Tevatron) to 700 V (2.2 eVs proton bunches), while that for the large bucket the heights were kept constant at 1500 V.

The figures 3 to 9 show typical results from simulations for 11 bunch coalescing in the MI. The beam and rf parameter used in this calculation were

3. parabolic bunches,
4. longitudinal emittance of the 53 MHz bunches at injection = 0.15 eVs,
5. Vrf(53 MHz) at 27 GeV after acceleration = 0.501 MV and is iso-adiabatically brought down to 7 kV before they are turned off. (bucket area at this stage ~ 0.36 eVs),

Table I: The Main Injector machine parameters.

Parameters	**Values**
Mean Radius of the Main Injector	528.3019 meters
Nominal γ_T	21.7
Beam Energy at injection Coalescing Energy Peak Energy	8.938 GeV (8.889 GeV/c) 27 GeV 150 GeV
Slip Factor η at 27 GeV	0.0009
Revolution Period T_0 Revolution Frequency f_0	11.13 μsec 89.812 kHz
Barrier bucket Parameters Small Bucket Large Bucket	 Barrier pulse width = 57 nsec Barrier pulse height = 340 V – 700 V Barrier pulse width = 310 nsec Barrier pulse height = 1.5 kV
RF systems V (53 MHz) V (2.5MHz)	 <4 MV ≤60 kV

4. small barrier bucket: V_{small} = 480 V, bucket area with no pulse gap =1.8 eVs and half bucket height ≈ 11.9 MeV,
5. the minimum synchrotron oscillation period for the beam particles in the small bucket was varying from 2.1 sec to 1.1 sec from beginning to the end of the compression depending on the pulse gap.

The beam compression at 27 GeV is carried out in 4 sec. The figures 4-7 show various stages of barrier bucket manipulation and the corresponding beam distribution. As the beam is compressed between small barrier buckets, the particles with half momentum spread >11.9 MeV will escape from the small bucket. The unique feature of this scheme is that as soon as they hit large barrier pulses, they are accelerated or decelerated rapidly away from the small barrier bucket and will escape from the region of interest. On the other hand the high density particles with low momentum spread will be captured in the small barrier bucket. The final longitudinal emittance of such bunch is found to be about 1.8 eVs and about 62% beam particle survive.

Table 2: The Main Injector 8 GeV – 150 GeV magnet ramp used in the simulations.

Time (sec)	Momentum (GeV/c)	dP/dt (GeV/c/sec)
.5	8.889	0
.5355	8.96	6
.57704	9.5	20
.72704	18.5	100
.84242	26.	30
.90909	27.	0
6.5091	27.	0
6.53577	27.08	6
6.74419	35	70
7.01446	60	115
7.49472	115	115.
7.73662	140.	90.
7.94973	149.59	0
8.1639	149.59	0

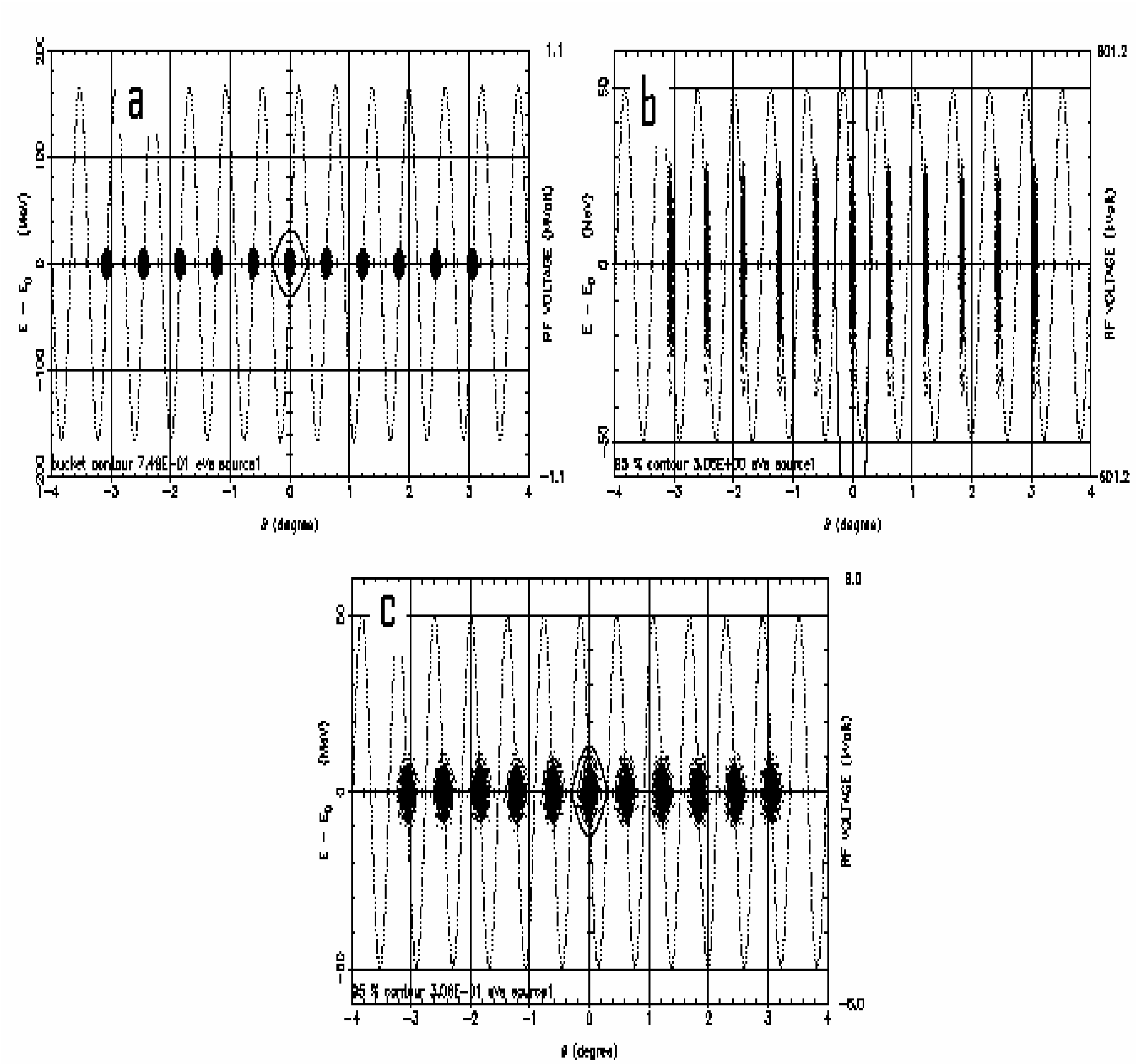


Figure 3: ESME simulation of ($\Delta E, \Delta\theta$)- phase space distribution of 0.15 eVs bunches from 8-27 GeV acceleration. a) at 8 GeV, b) at 27 GeV before iso-adiabatic reduction of the 53 MHz rf voltage and c) after the 53 MHz rf voltage is dropped down to 7kV. The horizontal axis shows the azimuthal coordinate of the beam in the Main Injector. The vertical axis shows the energy offset from the synchronous particles. The dotted lines represent 53 MHz rf wave forms and closed contour around the central bunch show the bucket. The buckets for the other bunches are not shown. This picture is common to both barrier bucket coalescing schemes presented here.

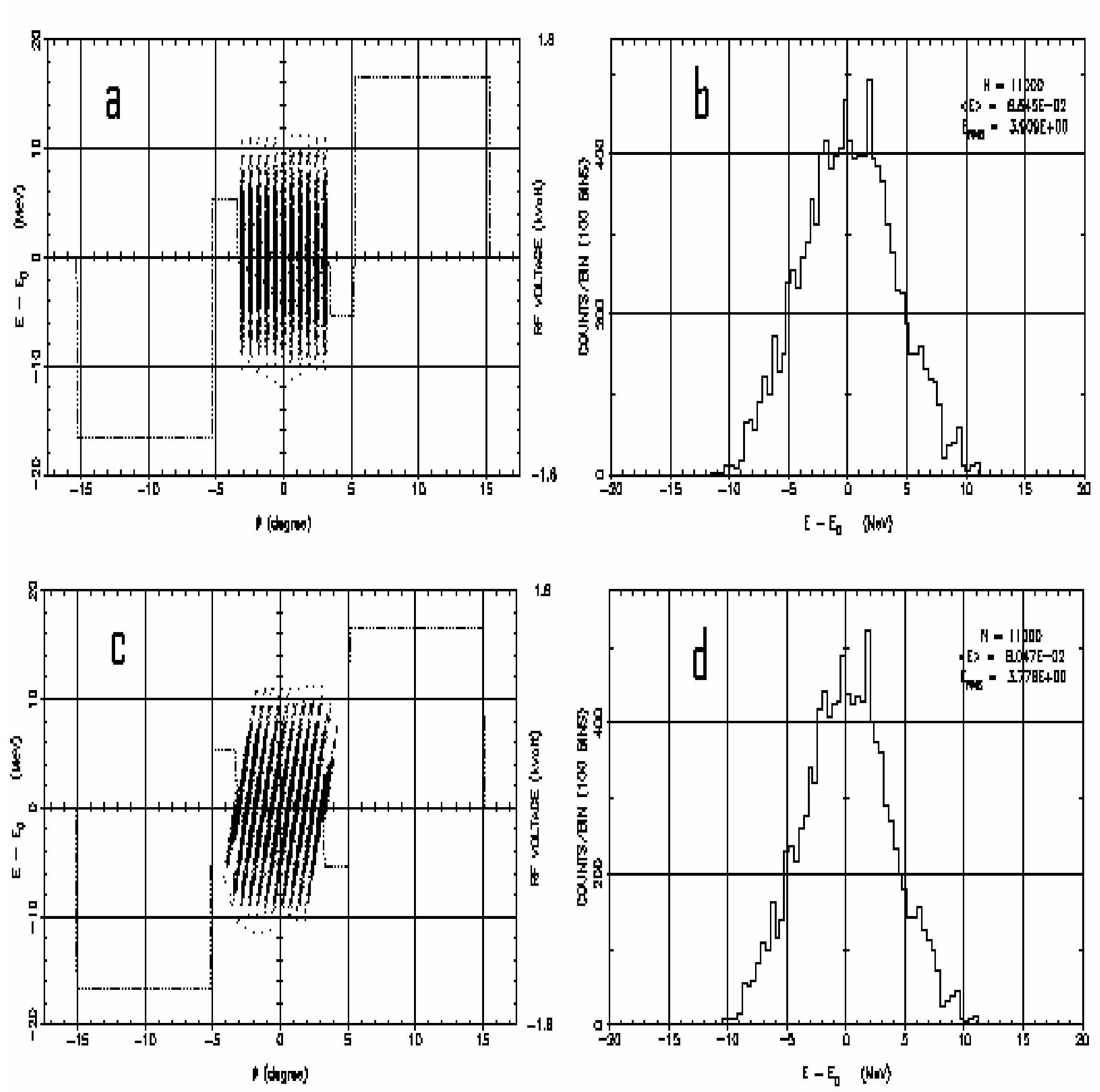


Figure 4: Barrier bucket Coalescing Scheme-1: ESME simulation of (ΔE,$\Delta\theta$)- phase space distribution for 11 bunches during the early stages of barrier rf buckets manipulations at 27 GeV. The energy distribution for each case (b and d) is shown below the phase-space distribution (a and c). In "a" and "c", the dotted curve shows the large and small barrier pulses.

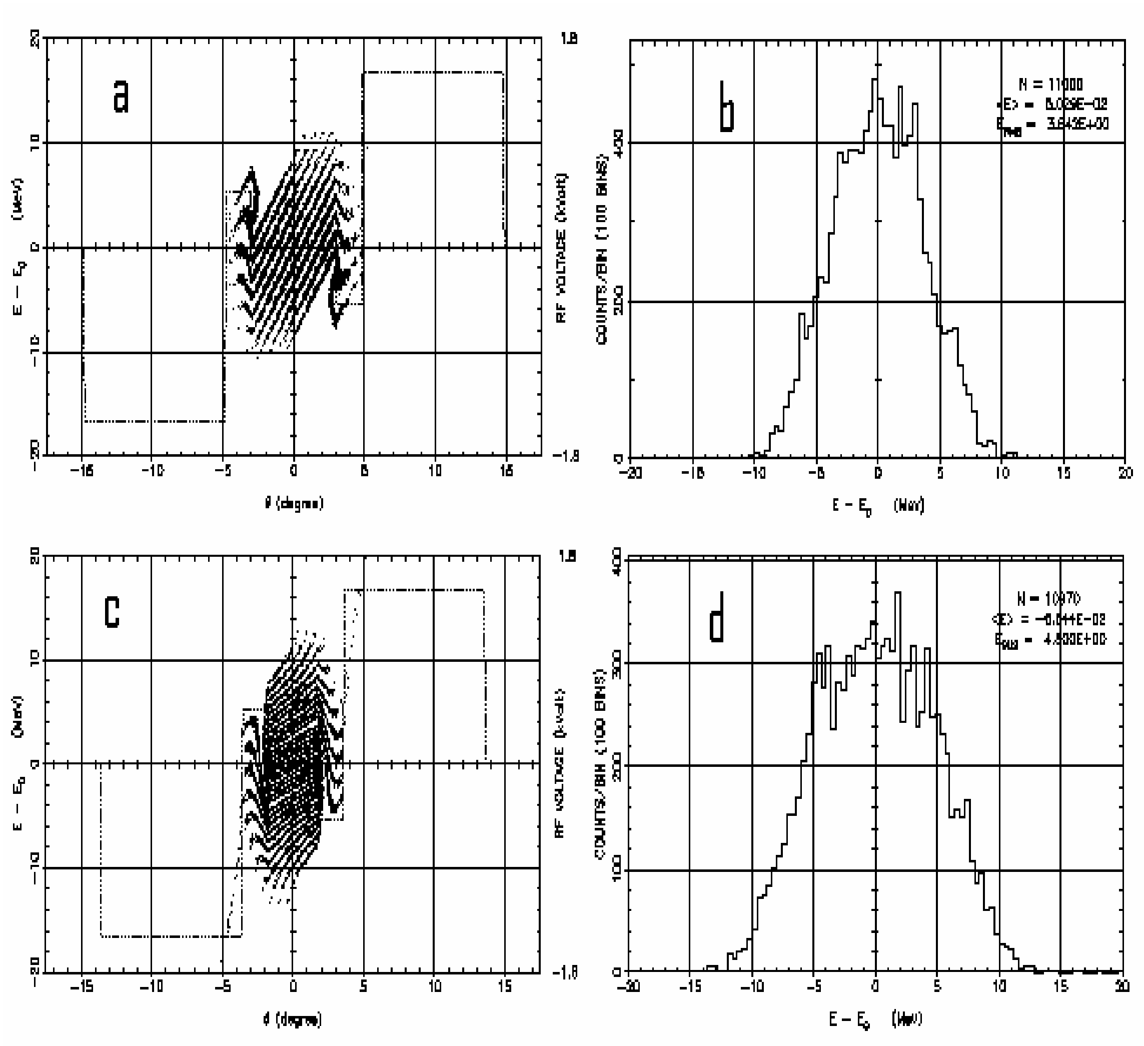


Figure 5: Description is very similar to that given in Fig. 3. “a” and “c” show the distributions at 0.44 sec and 1.21 sec after barrier rf compression starts.

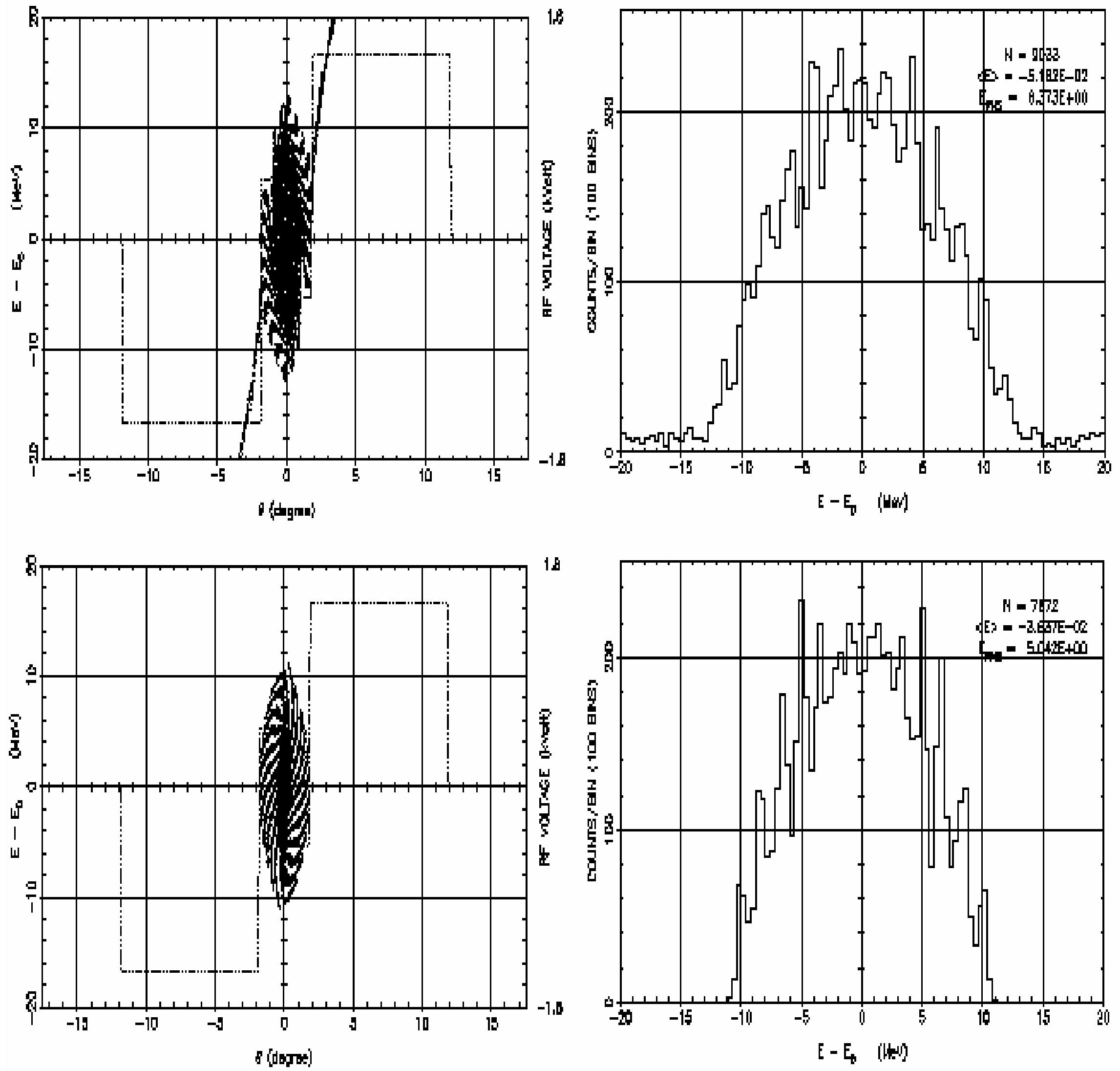


Figure 6: Description is very similar to that given in Fig. 3. "a" and "c" show the distributions at 2.55 sec and 3.21 sec after barrier rf compression starts.

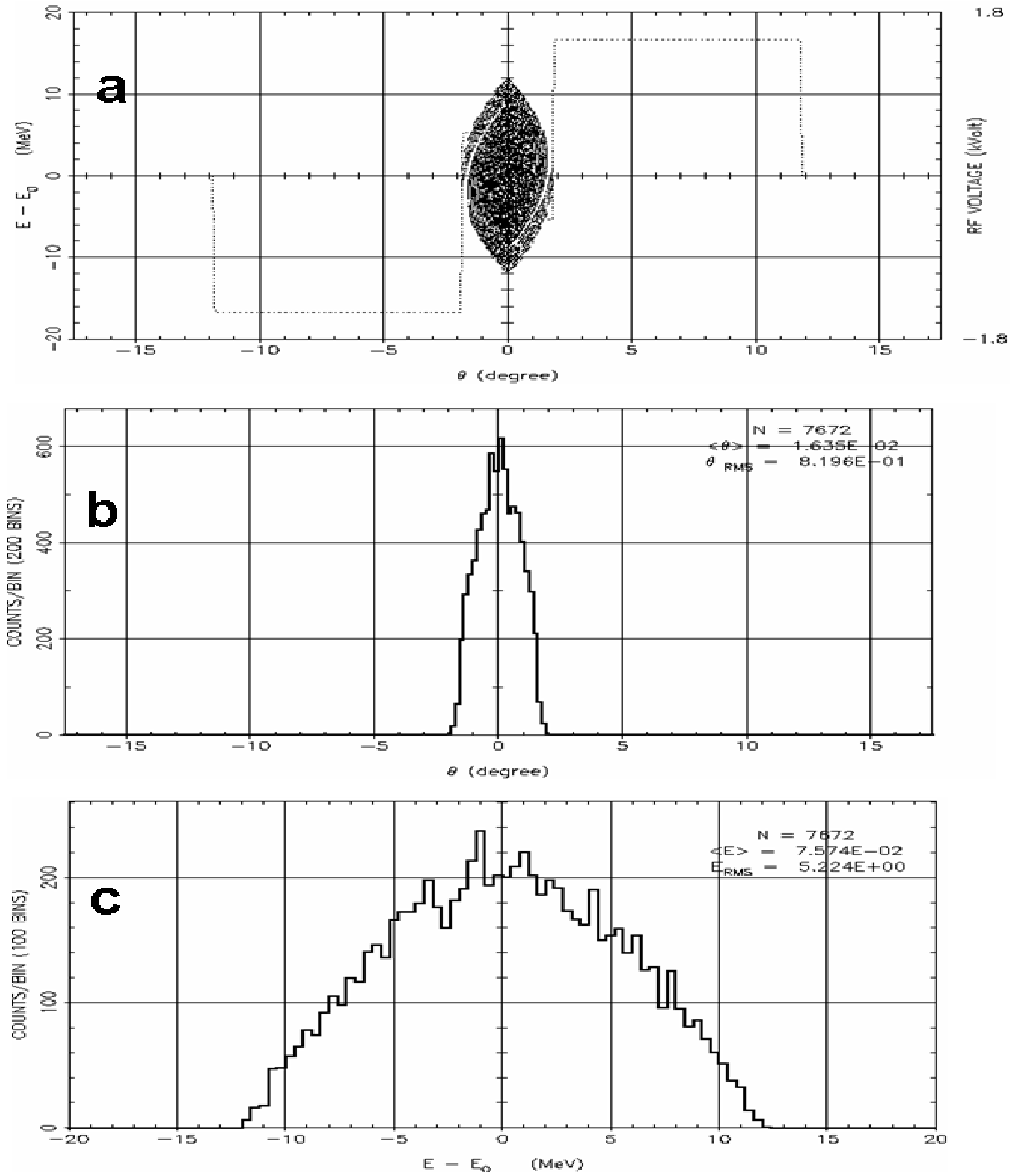


Figure 7: Phase space distribution, azimuthal projection and energy distribution of the captured beam at 0.5 sec after the end of barrier compression. Other details are similar to that in Fig. 3.

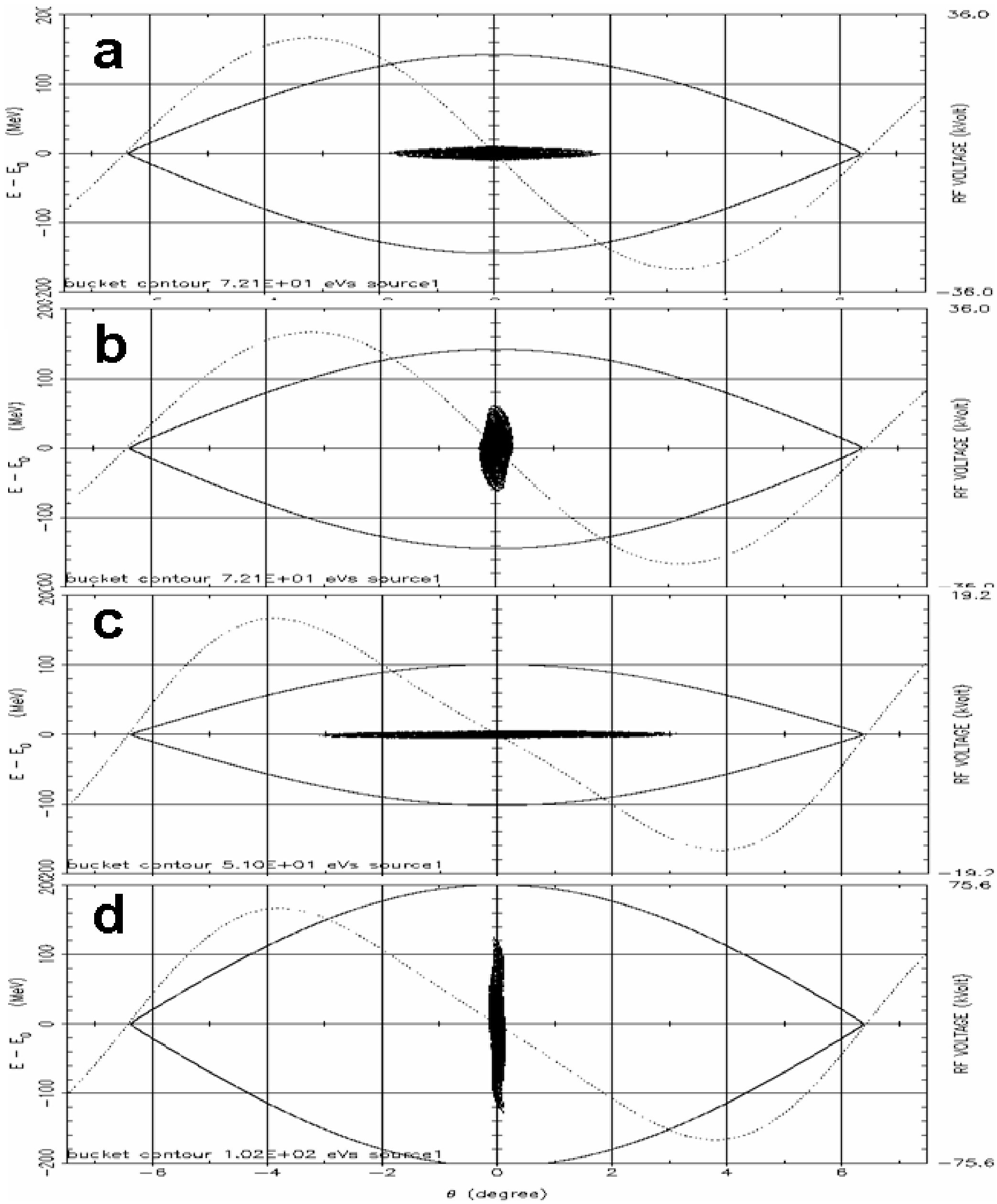


Figure 8: ESME prediction of beam particle distributions during 2.5 MHz rf manipulation a) first instant of capture of the beam from the barrier bucket (Vrf(2.5MHz)≈ 30kV), b) after a quarter rotation, c) another quarter rotation with reduced rf voltage (Vrf(2.5MHz)≈15kV and Vrf(5MHz)≈3kV), and (d) last rotation with increased rf voltage (Vrf(2.5MHz)≈60kV and Vrf(5MHz)≈10kV).

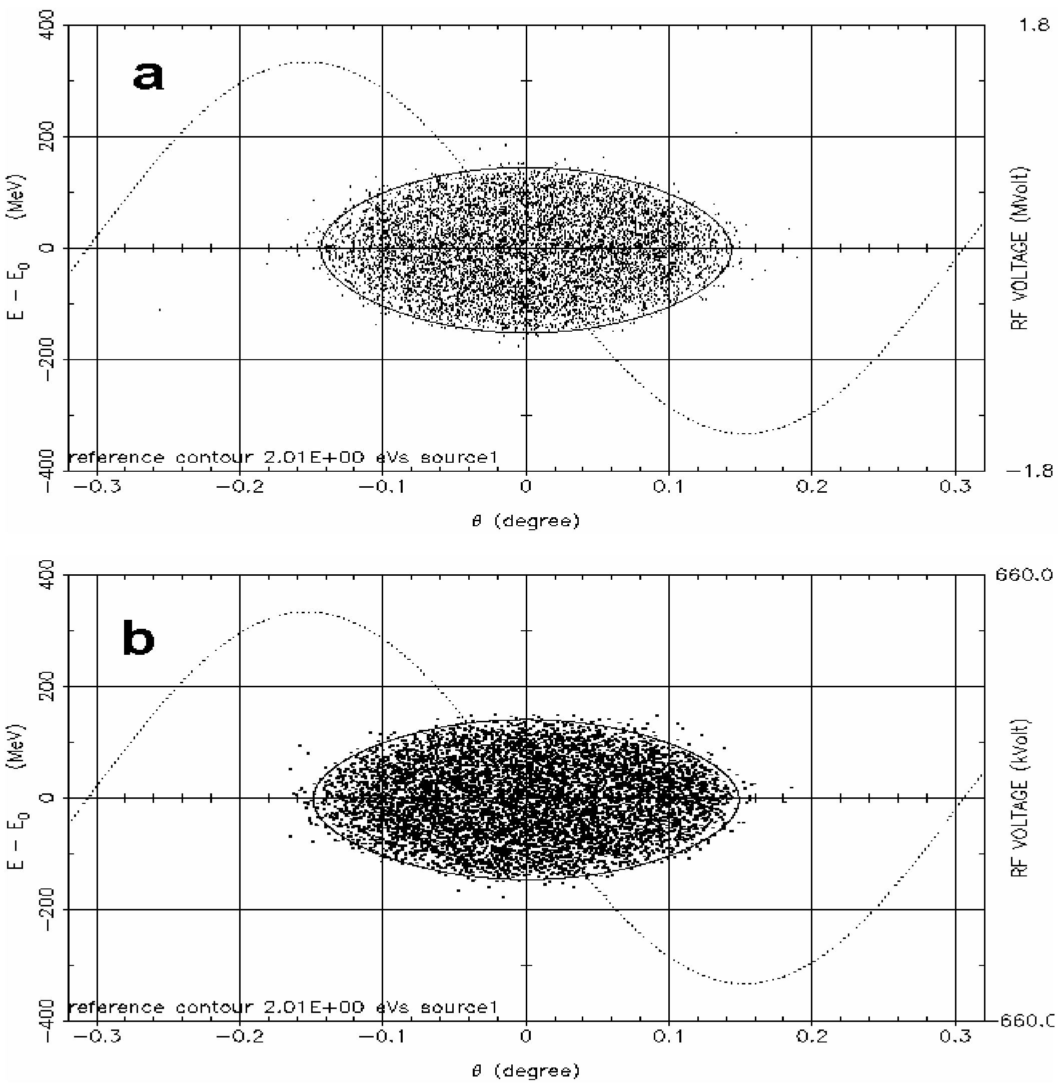


Figure 9: The beam distributions in 53MHz bucket a) just before acceleration from 27 GeV and b) at 150 GeV flat top, before transfer to the Tevatron. The closed contours represent 2 eVs phase space area which is about 98% emittance. The 95% emittance is about 1.8 eVs. Total bunch intensity at 150 GeV was about 340×10^9 protons.

The final high intensity bunch in the small barrier bucket is found to be about 110 nsec and is transferred to a 2.5 MHz rf bucket of about 30 kV. The simulation showed no noticeable emittance growth during this transfer. In the next 0.150 sec the bunch is transferred to a 53 MHz rf bucket with V(53MHz) ≈ 0.7 MV. Figure 7 shows various steps involved during this time interval. In the simulations we find no emittance dilution or beam particle loss during the 2.5 MHz rf manipulation at 27 GeV to the end of the acceleration cycle at 150 GeV in 53MHz rf buckets. The particles not captured in the central bucket will be captured in 53 MHz buckets and sent to MI abort after the central bunch transfer to the Tevatron.

In the context of the present operation of the MI, typical operating scenario allows us to get eleven 53 MHz bunches of 0.15 eVs with about 50×10^9 protons each from the Fermilab Booster at about 15 π-mm-mr. As per the simulation presented here, we can transport about 340×10^9 protons per 53 MHz bunch with longitudinal emittance of 1.8 eVs (95%) to the Tevatron once every 10 sec. Since the coupling between transverse and longitudinal beam dynamics is negligible we expect transverse emittance to be un-affected.

Figure 10-11 summarize the simulation results for a range of parameters for different number of bunches at injection, initial distributions and range of final longitudinal emittance. It is quite clear that better the debunching before the barrier rf manipulations higher the intensity for the final 53 MHz bunch.

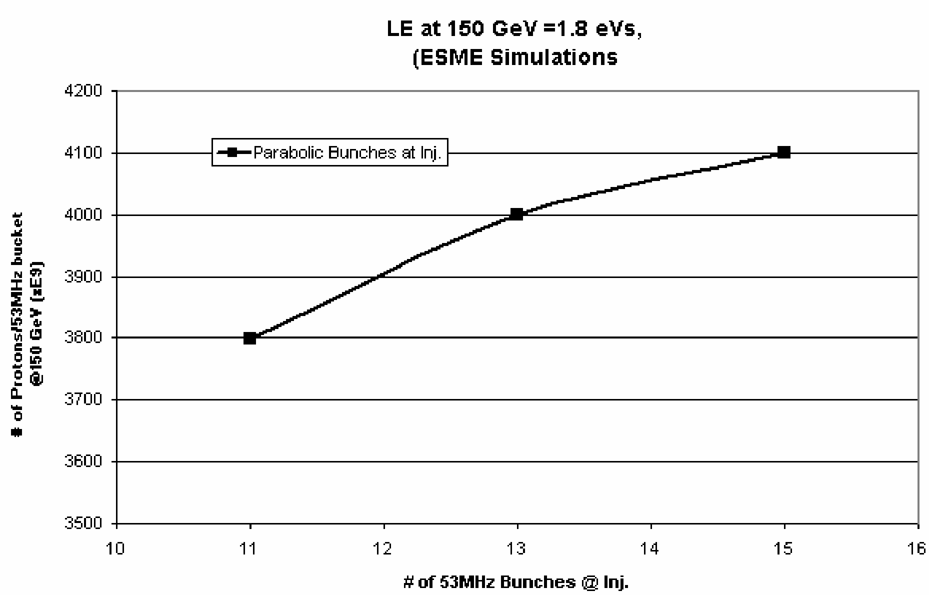
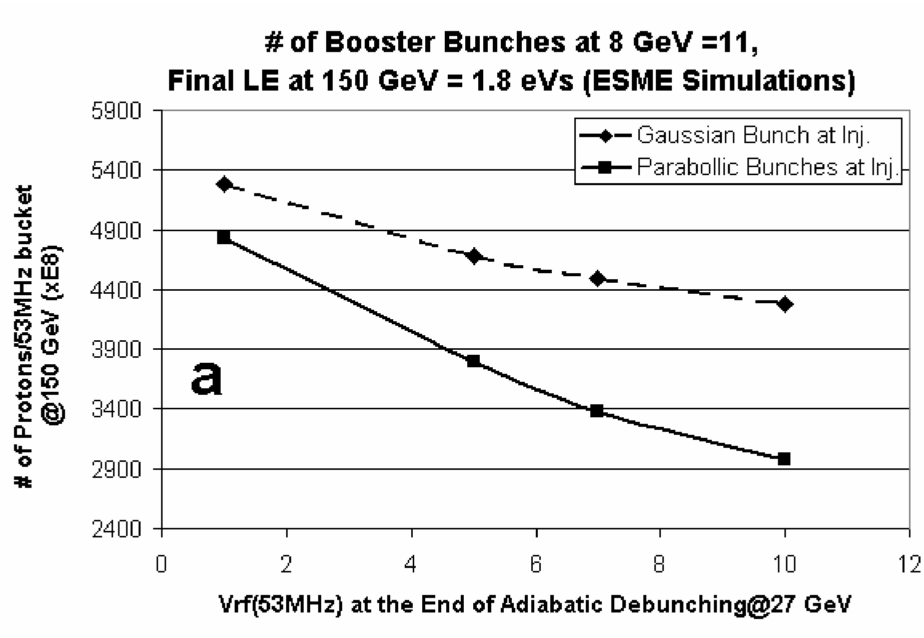


Figure 10: ESME simulations for final 53MHz bunch intensity as a function of number of 53 MHz bunches at 8 GeV. Vrf(53 MHz) at the end of iso-adiabatic debunching at 27 GeV is assumed to be 5 kV. If the Vrf(53 MHz) is reduced only up to 7 kV then the beam particles in the final 53MHz bucket will be about 11% smaller than the one shown here.



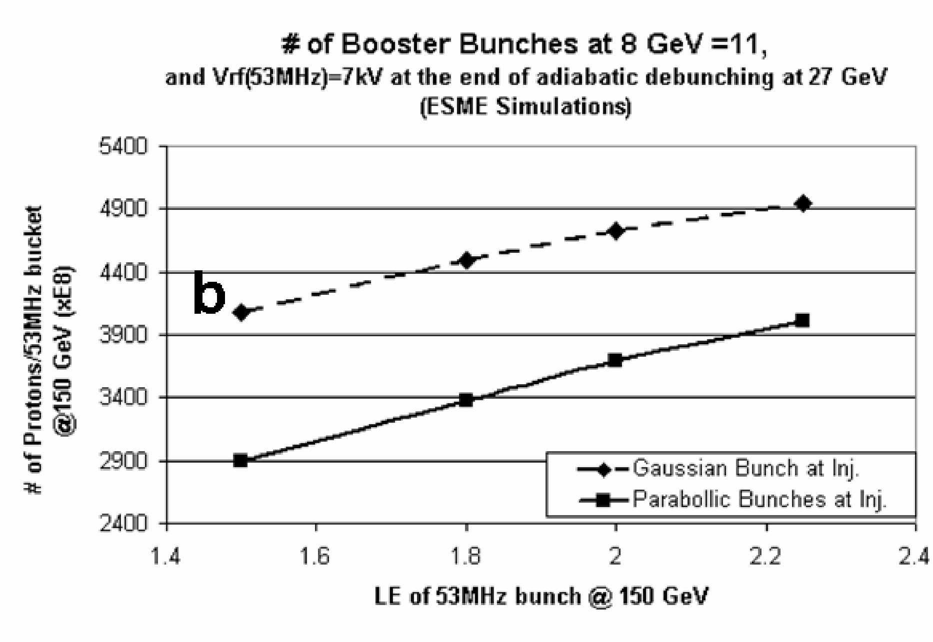


Figure 11: ESME simulations assuming Gaussian and parabolic distributions for beam particle at 8 GeV. The number of bunches are assumed to be 11 for all these calculations.

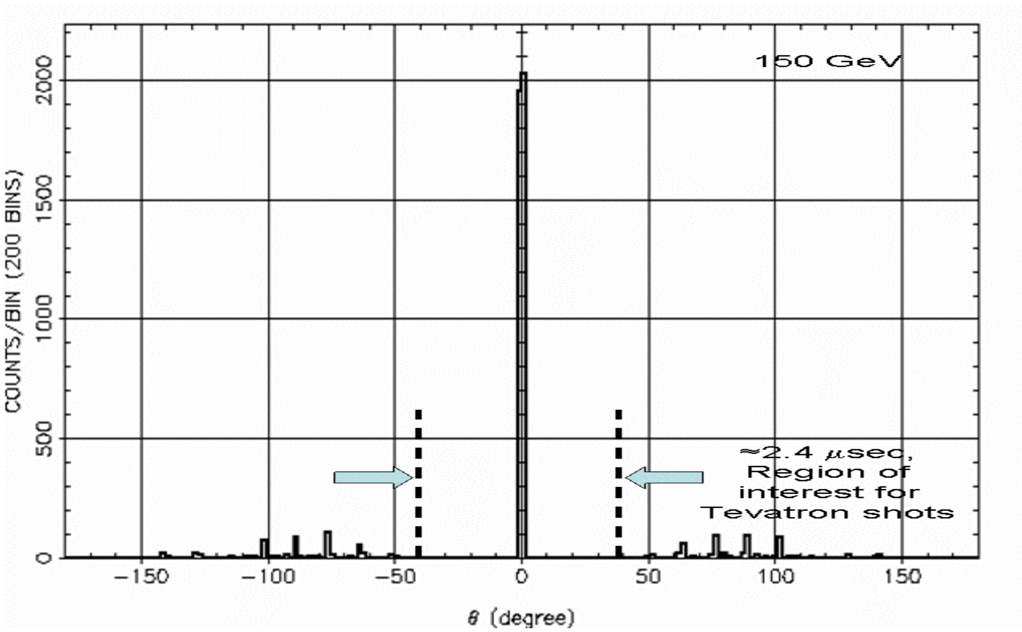


Figure 12: ESME simulation of beam particle distribution around the MI at 150 GeV. This clearly shows no beam for about 3μsec around the central 53MHz bunch.

From our simulations (see figure 10 and 11) we find that about 30-50% of the beam particles will escape from the small barrier and will be roaming around the MI outside the barrier bucket separatrices. Since the minimum synchrotron period for the beam particles in the large barrier bucket is ≈13 sec, the escaped particles will be slowly drifting away from the small bucket with a momentum spread of about ±50MeV and in about 4 sec they will be somewhere on the other side of the ring. At the end of 27 GeV rf manipulations those particles will also be captured along with the main bunch (notice that the height of the 53 MHz bucket with Vrf(53 MHz) = 0.7 MV is about ±150 MeV, which is much larger than that for the freely roaming particles). Figure 12 shows the final distribution of beam bunches around the ring at 150 GeV. Since the MI kicker flat top is ~1.6 μsec and no dc beam in about 2.4 μsec around the intense bunch, the beam transfer the Tevatron will be very clean.

III.2 Barrier Bucket Coalescing Scheme -2:

Here, we illustrate with a simulation for a case with nine bunch coalescing. The simulation results for 8-27 GeV for this case is identical to Scheme -1. The figure 13a shows nine bunches in 53MHz buckets with Vrf(53MHz) = 10 kV at 27 GeV. We turn off

53 MHz rf system and turn on the barrier buckets as shown in figure 13b. In the next 3 seconds the barrier rf voltage for the intermediate bunches are turned off slowly and linearly while reducing the last small barriers on both sides to about 400 V. The area of the barrier bucket imbedded between large barriers is chosen to be about 1.5 eVs. By adjusting the height of the small barriers one can vary the bucket area. The end result is shown in figure 13c. The simulation showed that about 87% of beam particles can be captured in the small barrier bucket. The bunch length is found to be about 200 nsec and $\frac{\Delta p}{p}$ about $\pm 1.5\times 10^{-4}$, which is quite good for the final 2.5MHz bunch rotation and capture in 53MHz.

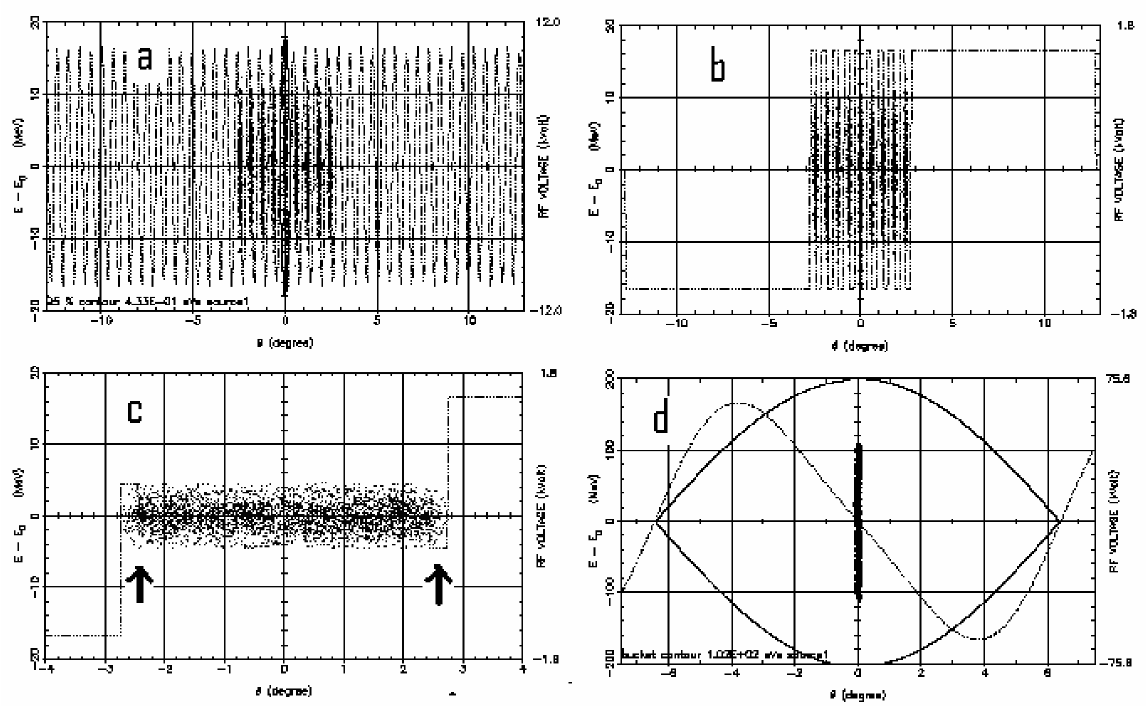


Figure 13: Barrier bucket Coalescing Scheme-2: ESME simulations. The pictures show phase space distributions at 27 GeV for various rf manipulations. a) 53 MHz capture after adiabatically reducing the Vrf(53MHz) from 0.5MV to 10 kV, b) capture in barrier buckets, c) after iso-adiabatic merging of the bunches between small barrier indicated by arrows and d)after rotation in 2.5 MHz bucket with Vrf(2.5MHz) = 60 kV + Vrf(5 MHz) = 10 kV.

A single bunch of about 1.6 eVs (95%) captured in 53 MHz bucket at 27 GeV is shown in figure 14a and b and the one at 150 GeV is shown in figure 14c. The rest will be retained in the 53 MHz buckets which are at about 1 μsec away from the central intense bunch. We find that for nine 53 MHz bunches of 0.15 eVs with about 50×10^{9} protons/

bunch about 390×10^9 protons about 1.7 eVs can be transferred to the Tevatron. In simulations we find that the Scheme-2 is about 30% better than Scheme-1.

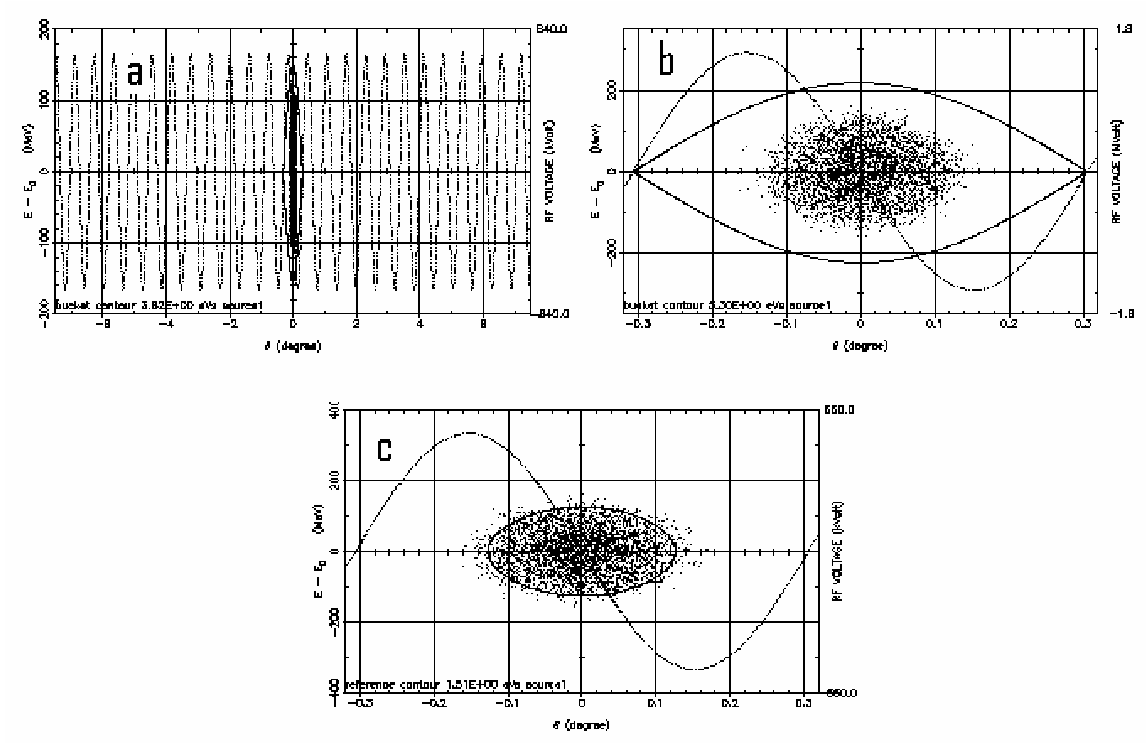


Figure 14: ESME simulation of beam particle distribution (continuation from figure 13) a) and b) at 27 GeV in 53MHz buckets and c) bunch at 150 GeV in 53MHz bucket. Contour is for 1.5 eVs. The 95% beam area is slightly larger than 1.5 eVs.

One can think of different variation of Scheme-2 which would help to get brighter beam bunch. For example, one can inject eleven or more (instead of nine) 53MHz bunches of 50×10^9 protons each. Then at 27 GeV open one rectangular barrier bucket for each 53MHz bunch and follow the procedure outlined above. But, compress the de-bunched bunch to 170 nsec or less the before iso-adiabatic rotation in 2.5 MHz bucket. By this we were able to capture about 10% more beam particles as compared with the simulations explained above.

There are several variations one can think of to speedup the rf manipulations at 27 GeV in both the barrier bucket coalescing schemes described above. For example, at 27 GeV one may drop the 53MHz rf voltage from 0.5 MV to about 60 kV and perform quarter synchrotron oscillation to reduce the $\frac{\Delta p}{p}$, instead of bringing Vrf(53MHz) iso-adiabatically to 10 kV.   From this we can gain about 0.5 sec in the entire cycle. And so on.

A few remarks on Space-charge and Wake-field Effects:

The simulations presented here are carried out using single-particle beam dynamics in which we have not included space-charge and/or wake-field effects arising from the rf cavities and the MI ring. In the final analysis these effects must be taken in to account. Here I have made some estimation of these effects.

During standard operation of the MI a typical 53 MHz bunch has an intensity of about 6×10^{10} protons, longitudinal emittance of about 0.15 eVs and line-charge density of about 200×10^{18} p/sec/eVs. Such a bunch is found to be quite stable against space-charge effect through any acceleration cycle. With the barrier bucket coalescing a bunch will be having intensity of about 5×10^{11} proton per 1.5 eVs and a line-charge density of about 53×10^{18} p/sec/eVs. Comparison between these two cases suggests that the space-charge effect will not be a problem.

Similarly, I have also investigated the Keil-Schnell limit for longitudinal microwave instability for a single bunch of about 6×10^{11} protons. Assuming a circular beam pipe of average radius of 5 cm and beam radius of 0.3 cm the space-charge impedance is $\leq 1.5\Omega$ from 27 GeV to 150 GeV, while the Keil-Schnell limit is orders of magnitude larger. Hence, space-charge instability is not of concern.

For high intensity bunches, the beam-loading effect due to rf cavities impedances can not be ignored. The R/Q for a 53 MHz cavity is about 104Ω. Thus an average induced voltage by a single bunch of 6×10^{11} for 18 rf cavities is about 60 kV (under impulse approximations). But the existing feed-forward and feed-back beam loading compensation will bring down the beam-loading voltage to ~1kV. Similarly, the beam loading compensation for the 2.5 MHz rf system bring the induced voltage from about 3.7 kV to <100 V. In the past we have carried out detailed ESME simulations for four bunch scenarios with bunch intensity of 1.7×10^{11} /bunch with realistic beam particle distributions [6]. An extrapolation of the results presented in ref. 6 to the present case suggests that the existing beam-loading compensation is quite adequate and beam-loading is not going to be a problem.

Thus, even with a bunch intensity of 6×10^{11} protons the space-charge and some of the wake-field effects do not seem to pose problems. Detailed simulations of these effects are in progress.

Implementation of this scheme in the MI:

Implementing these scheme in the MI is quite straight forward. We have all necessary hardware in place. Presently, a wide-band rf cavity system is being used a as bunch by bunch longitudinal damper for 53MHz and 2.5MHz bunches at injection and during beam acceleration in the Main Injector. These cavities can produce up to 1.8 kV per turn. One can use them as longitudinal bunch dampers from 8 GeV to 27 GeV and then use them as barrier rf systems at 27 GeV for bunch manipulations and again as dampers from 27 GeV to 150 GeV acceleration. Some software development for barrier rf manipulation at 27 GeV is needed.

III.3 27 GeV Coalescing

Simulation have been carried out for coalescing seven 0.15 eVs bunches at 27 GeV both for adiabatic coalescing [18] and snap coalescing. The results are very similar to the one carried out at 150 GeV [19]. In this method one will not be able to select the low emittance high density region of the beam particle distributions. As a result of this one ends up in quite large longitudinal emittance 53 MHz bunch. If the bunch intensity is quite large one may be able to momentum scrape during acceleration from 27 GeV to 150 GeV by selecting the acceleration bucket area at one or two points in the cycle. However, getting intense bunch may be quite challenging. The advantage of this method over the 150 GeV coalescing [2] is that no dc beam will be left in the MI at the time of beam transfer to the Tevatron. The disadvantage is that achieving proton beam intensity and longitudinal emittance requirements set earlier is very difficult.

A beam experiment on 27 GeV coalescing was conducted in the MI [20] during the commissioning of the “pbar 2.5MHz slow acceleration” project [6]. The figure 15 (top) shows typical results from such experiment. The magnet ramp (indicated by “P GeV/c”) is very similar to that shown in Table 2 with a shorter (1.5sec) 27 GeV front-porch. In this preliminary effort the maximum beam captured in a single bunch was about 210×10^{9} proton. The longitudinal emittance was about 3 eVs at 150 GeV. Wall current monitor data (using SDA) from 8 GeV to 150 GeV is shown in figure 15 (bottom). I believe that it is worth-while to investigate further the feasibility of this scheme for the Tevatron shots.

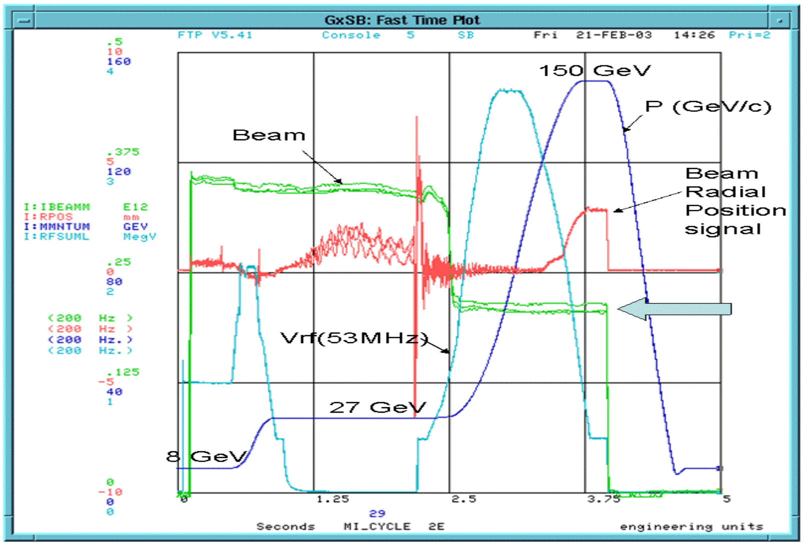


Figure 15: 27 GeV coalescing of seven 53 MHz bunches. The average bunch intensity at injection was about 50×10^{9} protons. In the top figure momentum ramp ("P GeV/c"), Vrf(53 MHz), beam intensity and radial position signal out-put are shown. The bottom figure shows the wall current monitor data at (a) at injection, (b) at 27 GeV before first rotation, (c,d) at 27 GeV during and after first rotation, (e) at 27 GeV soon after 53 MHz capture, (f) at the start of 27-150 GeV acceleration and (g) at 150 GeV

IV Summary

The Run II upgrade plan has led to several improvements in the performance of the collider complex to maximize the proton-antiproton luminosity. It is evident that by injecting proton bunches of longitudinal emittance ≤2 eVs and intensity of about 300×10^9p/53MHz bunch each the peak luminosity can be increased by ≥20%. Here, I have proposed two schemes to achieve both proton intensity and longitudinal emittance goals. Of the schemes, the barrier bucket coalescing schemes are very promising. In the first scheme a number of 53 MHz proton bunches are captured between two sets of rectangular barrier buckets at 27 GeV in the MI. They are compressed iso-adiabatically and the intense region of the bunch phase-space is isolated for final use. In the second scheme every bunch is captured in a barrier bucket at 27 GeV with two large barrier buckets around. These bunches are iso-adiabatically de-bunched. In the simulation we find that the second scheme has higher efficiency in terms of number of surviving beam particles and results in smaller longitudinal emittance. In both the schemes, the particles with large momentum spread can be aborted very cleanly. Simulation shows that one can achieve in access of 300×10^9protons/53MHz bunch with longitudinal emittance ≤2 eVs (95%) for the Tevatron collider shots.

Another important factor in increasing the proton-antiproton luminosity in the Tevatron is reducing the transverse emittance of the beam. The transverse emittance is found to be well maintained in the MI during the acceleration. With the barrier bucketcoalescing scheme in place one can scrape transversely up to 25% of the beam in the tail region of the transverse space and produce lower transverse emittance. This will further increase luminosity over the gains from reduced longitudinal emittance and increased N_p.

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